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USE OF AN ANALOG MODEL FOR DETERMINATION OF VENTILATION
AND AIR DISTRIBUTION IN THE LUNGS

by

M. Navratil

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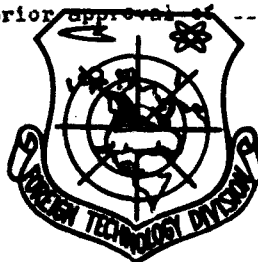
USE OF AN ANALOG MODEL FOR DETERMINATION OF VENTILATION
AND AIR DISTRIBUTION IN THE LUNGS

By: M. Navratil

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ABSTRACT
        The lungs represent a space in which the air is chanelled into innumerable alveolar units. Distribution of air is not uniform even in healthy lungs, the less so in disease with differently ventilated regions.
        For comparison we used an analogous model with a definitely determined programme: functional residual capacity and ventilatory turnover of a certain investigated subject. Nitrogen clearance during oxygen inhalation was measured by continual nitrogen analysor. A spirometer was used as the model; identical ventilation as exhibited by the trial subject was performed with it. The pair--lung-model--corresponds to the simple type of analogous computer with an invariable programme for a given purpose. These trials were conducted in 95 subjects with a variety of disorders in order to derive relations of effective lung ventilation and effective model ventilation. Results obtained revealed a greatly increased efficiency of ventilation in healthy subjects and patients with interstial fibrosis, whereas patients with advanced silicosis showed distribution patterns in their lungs approximating those in the model. However, in patients with obstructive emphysema, relations--lung--model were reversed. Unevenness of distribution in emphysematous lungs is the conclusion drawn from this observation. Bronchial obstruction prevents the inflow of air into hypoventilated lung regions.

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Institute of Industrial Hygiene and Occupational Diseases, Prague.
Prof. Dr. J. Teisinger, Director

USE OF AN ANALOG MODEL FOR DETERMINATION OF VENTILATION AND AIR DISTRIBUTION IN THE LUNGS

M. Navratil

Statistical Analysis by Z. Roth

ABSTRACT: The lungs represent a space in which the air is channelled into innumerable alveolar units. Distribution of air is not uniform even in healthy lungs, the less so in disease with differently ventilated regions.

For comparison we need an analogous model with a definitely determined program: functional residual capacity and ventilatory turnover of a certain investigated subject. Nitrogen clearance during oxygen inhalation was measured by continual nitrogen analyser. A spirometer was used as the model, identical ventilation as exhibited by the trial subject was performed with it. The pair—lung-model—correspond to the simple type of analogous computer with an invariable programme for a given purpose. These trials were conducted in 25 subjects with a variety of disorders in order to derive relations of effective lung ventilation and effective model ventilation. Results obtained revealed a greatly increased efficiency of ventilation in healthy subjects and patients with interstitial fibrosis, whereas patients with advanced silicosis showed distribution patterns in their lungs approximating those in the model. However, in patients with obstructive emphysema relations—lung—model were reversed. Unevenness of distribution in emphysematous lungs is the conclusion drawn from this observation. Bronchial obstruction prevents the inflow of air into hypoventilated lung regions.

Research on the respiratory functions is usually carried out analytically by determining the individual partial mechanisms of the complex function of respiration and drawing conclusions from these partial results regarding disorders in a certain region of the physiological system examined. The final result of the examination then follows from synthesis of the partial results and permits determination not only of the site of the disorder, but also its degree, and thus brings asthma, as a reflection of respiratory disorder, closer to objective diagnosis.

In our study we have used a different approach. First we examined a given patient to determine the ratio of the unit static and dynamic ventilations as the "effective ventilation" figure and then duplicated this process on a suitable analog model with a precisely defined program. Comparison of the results gave us the effective pulmonary ventilation for the patient examined.

What is to be understood by the term "analog model?" Briefly stated, it is a simple kind of analog computer available to any cardio-pulmonary laboratory. It is well known that an analog computer operates on the principle of a suitably composed program based on examination of the desired functional values of the patient. The analog computer processes this information and simultaneously compares it with a standard program that passes through its functional mechanism. By comparing the results, the deviation

of the desired function of the patient can be determined qualitatively and quantitatively. In our country, this method has been employed by Sova and Kora [5] in calculation of radio-circulographic values.
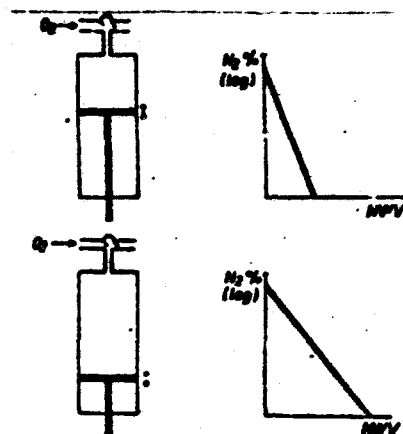

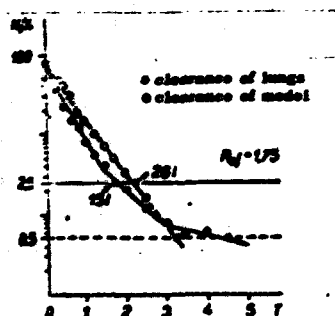Fig. 1. Model of N_2 clearance of two regions with different volumes.

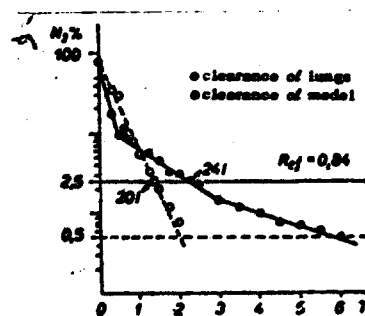Fig. 2. Nitrogen clearance of lungs and model for a healthy subject (Normal No. 8).

Fig. 3. Nitrogen clearance of lungs and model for an emphysema patient (Emp. No. 18).

We do not use an analog computer, but only a system built on the same principle — therefore an analog model. It is a simple, precisely defined space in which air exchange can take place. This takes the form of a water spirometer with a cylindrical chamber. Thus there is no similarity here to the pulmonary space, which is divided into numerous space units — the alveoli — but only a precisely defined space, i.e., a cylinder filled with air. Since the ventilation of a cylinder is easily represented and is reproducible, for example on an engineering-pneumatics basis, conclusions can be derived regarding the ventilation and distribution of air in the lungs of a patient by comparing the results (lungs and model).

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The fixed program put into the analog model was determined by the functional residual capacity of the patient and the ventilation turnover, in which the patient was breathing oxygen in the procedure used for determining lung clearance. In this way, the effective ventilations of the lungs and the corresponding model could be compared and the calculations used for inferences as to ventilation and distribution of air in the lungs of the patient.

Method and Results

The examination was carried out with an open-loop system; nitrogen clearance was measured with a Waters continuous nitrogen analyzer, as described earlier [1]. We carried out two determinations for every examination procedure. First the patient in question was examined and his effective ventilation determined. Then the analog model, set to the desired volume and artificially ventilated by oxygen with a desired ventilation turnover, was connected into the system in the patient's place in such a way that both program constants determined in the examination of a patient were preserved. This lungs-model combination gave us two nitrogen-clearance lines, from which we drew conclusions as to the subject's effective pulmonary ventilation.

The operation of the analog model is indicated in Fig. 1. In the first case, which represents the normal state, the piston marks off the extent of the functional residual capacity, which is not even half the total capacity. During respiration, described by the motion of the piston, a relatively small volume is ventilated and the corresponding nitrogen-clearance line therefore has a very steep slope (on a semilogarithmic scale). Only a small amount of oxygen is needed to flush the nitrogen out of the lungs. In the second case, the total capacity is identical but the functional residual capacity is considerably increased, as is the case in emphysema; the nitrogen clearance is slow and has only a moderate slope. The basal level of expired nitrogen is attained only after supplying a large amount of oxygen.

The ratio of the static and dynamic ventilation units — the effective ventilation — was used as the comparison quantity. In earlier studies (Navratil [2, 3]), we had found by theoretical analysis and practical application to a group of subjects that the ratio of total capacity (TC) to the amount of oxygen necessary to flush nitrogen out of lungs to the basal level of 2.5% N_2 (NWV, Nitrogen Washout Volume) represents, in a form of a fraction, the portion of the lung space that is effectively ventilated. The closer the fraction approaches to unity, the larger the portion of the lung space that is effectively ventilated.

In a healthy subject, the distribution of the inhaled oxygen, which eliminates nitrogen from the lungs, is rapid, and it soon fills all the alveolar spaces. The distribution of oxygen in the model is uniform, since a precisely defined cylindrical space is being ventilated; it is not rapid, because there is only one large space instead of the aggregate of small unit spaces characteristic for the lungs. The uniformity of distribution in the model manifests as a straight nitrogen-clearance line in semilogarithmic co-

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ordinates. Its slope, however, is smaller than the slope of the lung-clearance curve of the corresponding healthy subject. In this case, the effective ventilation of the lungs is more perfect and the curve of nitrogen clearance reaches the basal 2.5% N_2 level earlier and after a smaller amount of oxygen has been inhaled than the nitrogen clearance curve of the corresponding model. The relation of the two curves is shown in Fig. 2.
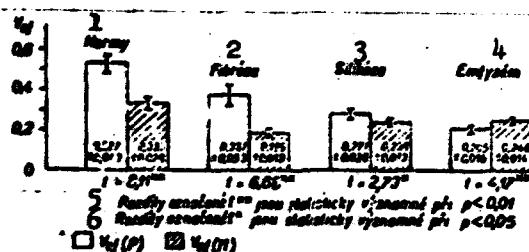
Fig. 4. Comparison of effective ventilations of lungs and analog model. 1) Standards; 2) fibrosis; 3) silicosis; 4) emphysema; 5) differences marked t^{**} are statistically significant with ...; 6) differences marked t^{*} are statistically significant with ...
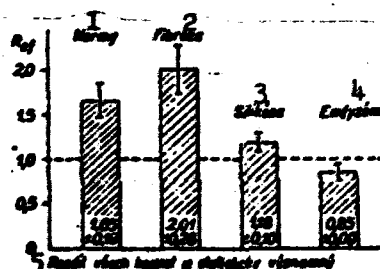
Fig. 5. Relation of effective ventilation of lungs to effective ventilation of model, if $V_{ef(m)} = \frac{V_{ef(p)}}{V_{el(m)}} \cdot R_{ef}$. 1) Standards; 2) fibrosis; 3) silicosis; 4) emphysema; 5) the distributions of all values are statistically significant.

The lungs of an emphysema patient have regions with nonuniform distribution and lowered ventilation; they release nitrogen only slowly. The curve of lung clearance is extended. The clearance of the corresponding model is faster, although only one large space is ventilated. It is obvious that regions with lowered ventilation in emphysematous lungs cause such nonuniform distribution that their clearance is slower than the clearance of the corresponding simple space (Fig. 3).

With this in view, we examined 95 subjects and the corresponding models: 21 healthy males 20-30 years old, 22 patients with interstitial fibrosis, 27 patients with advanced silicosis and 25 patients with chronic bronchitis and symptoms of obstructive emphysema. All were examined clinically, x-rayed, and tested spirographically; in all cases, residual volume and total capacity

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were determined and effective ventilation calculated. The results
on the effective ventilation were compared with the corresponding
model. We employed the Duncan test for statistical evaluation.

In the group of healthy males and fibrosis patients, the ef-
fective pulmonary ventilation quite significantly exceeds the ef-
fective ventilation of the model (Fig. 4). In the group of sili-
cosis patients, the difference is less significant, serving as
evidence that there are regions in silicotic lungs with lowered
ventilation which lead to the protraction of lung clearance. The
converse was found in emphysema patients, where the effective ven-
tilation of the model was significantly better than the effective
ventilation of the lungs. This finding points to a considerable
nonuniformity of air distribution in emphysematous lungs, in which
the regions beyond the bronchial obstruction show very poor air
exchange, with all its unfavorable symptoms at the level of alve-
olar ventilation and gas diffusion.

If, for each case examined, we take the effective ventilation
of the model as equal to 1, then the converted effective pulmonary
ventilation ratio will be larger than, smaller than, or equal to
1. The equation applying here is

$$\frac{V_{ef}\ Lungd}{V_{ef}\ (Model)} - R_{ef} \overset{>}{\underset{<}{=}} 1$$

For each of our 4 groups, the average R_{ef} is a number indi-
cating the degree of distribution uniformity (Fig. 5). It is obvi-
ous that healthy persons and, to a still greater degree, fibrotic
patients have highly effective ventilation; this is maintained in
fibrotic patients by increased ventilation turnover and utiliza-
tion of the reduced lung space for ventilation. The decrease in
effective ventilation in silicosis and, in particular, in empny-
sema is evidence of a substantially decreased ventilation function
that cannot guarantee the distribution of air into all lung re-
gions.

Discussion

We found that the effective pulmonary ventilation is higher
than the effective ventilation of the corresponding model space
for all healthy subjects and for some pathological states. The
relation was reversed only in patients with obstructive emphysema
and some severe cases of silicosis. What do these results repre-
sent?

1. Air distributed by the respiratory system into the numer-
ous small alveolar spaces mixes with the air contained in them
much more rapidly than in the corresponding ventilation of one
large cylindrical space. The organism thus promotes regeneration
of the alveolar environment with minimum effort. This may even be
aided by the action of the smooth muscles of the bronchial walls
and lung interstices during respiration.

Ventilation in one large space is uniform but not too effec-
tive, as in the case of the analog model. This phenomenon is well-

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known from pneumatic experiments on models with one air inlet in comparison to several inlets [4]. The plot of model clearance is exponential, or a straight line in semilogarithmic coordinates. Pulmonary ventilation is not uniform in any case, even in healthy persons. Therefore, it is expressed as a composite exponential line, and on a semilogarithmic scale usually as a thrice-broken line.

The lungs of a healthy subject can utilize the inhaled volume very effectively for the alveolar ventilation proper. Considering that the average functional residual capacity of a healthy human is 2.5 liters, the 0.5-liter volume of inhaled air must be distributed over a volume five times as large. It is necessary to distribute a relatively small volume of air into numerous spatial units, the alveoli, in order to achieve effective gas exchange at the alveolus/capillary-membrane interface. The difference between lung ventilation and the same ventilation of a simple space is quite evident here.

2. How do we explain the results for obstructive emphysema or advanced silicosis, where we find an effective ventilation lower than in an experiment on a corresponding model? It is this finding which supports our still vague conception of nonuniform distribution in the above pathological states. Beyond the bronchial obstruction, emphysematous lungs have regions with minimal gas exchange and hence with alveolar hypoventilation. The distribution of air is quite insufficient and the ventilation turnover of these regions is lowered to such a degree that it slows down the nitrogen clearance more than would correspond to a simple model space. Therefore, it is not only a matter of relatively large cavities in emphysematous lungs, as is known from pathological-anatomy preparations, but, in addition, an obstruction must be present, either of spastic nature, or in the form of phlegm, or, finally, in deformation of bronchi in the vicinity of silicotic nodules, which largely closes off the ventilation paths to the more remote alveolar spaces.

These conditions can again be represented in a patient with emphysema whose average functional residual capacity is 4 liters. It is known that these patients do not increase ventilation by expanding inhaled volumes, but rather by increasing the frequency, which causes an additional increase in the ventilation of the dead space. Nevertheless, if we assume the same 0.5-liter respiratory volume, it is then necessary to distribute this dose over eight times the volume! The effectiveness of this ventilation slowly approaches the effectiveness of ventilation of an empty space.

If we imagine all lung regions to be ventilated simultaneously in respiration, but with varying effectiveness, then we shall not question the findings of the model experiments in the above pathological states, or wonder why poorly ventilated regions prevail there, with all their consequences for alveolar ventilation and the ratios of the gases in the arterial blood.

Study of processes in the field of air distribution led us to suggest the term "effective ventilation." We know now, after examining additional clinical material, that the effective venti-

lation is closely connected with alveolar ventilation derived from the proportions of CO_2 expired and present in the arterial blood. In this way we arrive at the following schematic picture of the relations between the processes:

1. ventilation of the lungs as a whole;

2. distribution of air into all regions, but with varying ventilation effectiveness;

3. regeneration of alveolar environment in dependence on the air supply from the dead space and on the supply of blood from the pulmonary-artery flow.

This study shows how the original theoretical problems are reflected in practical clinical application and clarify the processes of air exchange in the lungs, which were hitherto only a subject of conjecture, but whose graphic demonstration has been made possible thanks primarily to use of the analog model.

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